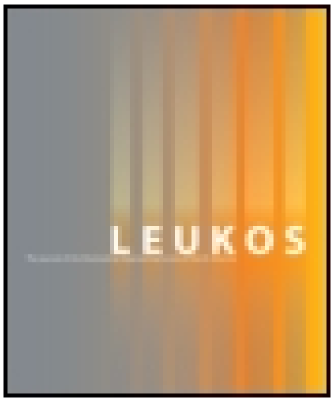

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Dynamic Daylight Performance Metrics for Sustainable Building Design

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Abstract—The objective of this document is to promote the use of dynamic daylight performance measures for sustainable building design. The paper initially explores the shortcomings of conventional, static *daylight performance metrics which concentrate on individual sky conditions, such as the common daylight factor. It then provides a review of previously suggested* dynamic *daylight performance metrics, discussing the capability of these metrics to lead to superior daylighting designs and their accessibility to nonsimulation experts. Several example offices are examined to demonstrate the benefit of basing design decisions on dynamic performance metrics as opposed to the daylight factor.*

Keywords—daylighting, dynamic, metrics, sustainable buildings

1 INTRODUCTION

Building performance metrics are supposed to be “quality measures” for buildings with respect to their energy efficiency, safety, quality of design, and so on. Performance metrics can be used for comparative studies to guide building design or to benchmark a building against a pool of other buildings. Performance metrics range from being rather specific, for example, how well are two building zones acoustically separated, to very general, for example, how “green” is a building. The latter type of metrics usually combines several individual submetrics into a single overall rating, stipulating a pass or fail criteria for each submetric[1]. Pass/fail criteria are effective at initially drawing the attention of the design team towards a specific issue such as “are there sufficient showers and bicycle racks in a building to allow staff to walk or cycle

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1 Prominent rating systems used in North America are LEED (www.usgbc.org/LEED/), Green Globe. (www.greenglobe21.com), and the Collaborative for High Performance Schools (http://www.chps.net/).

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to work" or "the proper way to set up an erosion and sedimentary control plan". They are more difficult to formulate and potentially less effective for more qualitative or multifaceted aspects of design, such as daylighting.

Daylighting is a notoriously difficult building performance strategy to evaluate. What is good daylighting? Research careers have been invested in answering this question. One of the difficulties of pinpointing good daylighting may be that different professions concentrate on different aspects of daylighting. Table 1

TABLE 1.
Five Sample Definitions for Daylighting (Reinhart C F and Galasiu A, 2006)

Architectural definition: the interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment
Lighting Energy Savings definition: the replacement of indoor electric illumination needs by daylight, resulting in reduced annual energy consumption for lighting
Building Energy Consumption definition: the use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting)
Load Management definition: dynamic control of fenestration and lighting to manage and control building peak electric demand and load shape
Cost definition: the use of daylighting strategies to minimize operating costs and maximize output, sales, or productivity

presents a sample list of definitions for daylighting that were presented to participants in a recent survey on the use of daylighting in sustainable building design (Reinhart and Galasiu 2006).

Figure 1 shows how a group of over 120[2] mostly North American and Australian building design professionals, who participated in the survey, rated which definition in Table 1 was most relevant to their work. Participants were

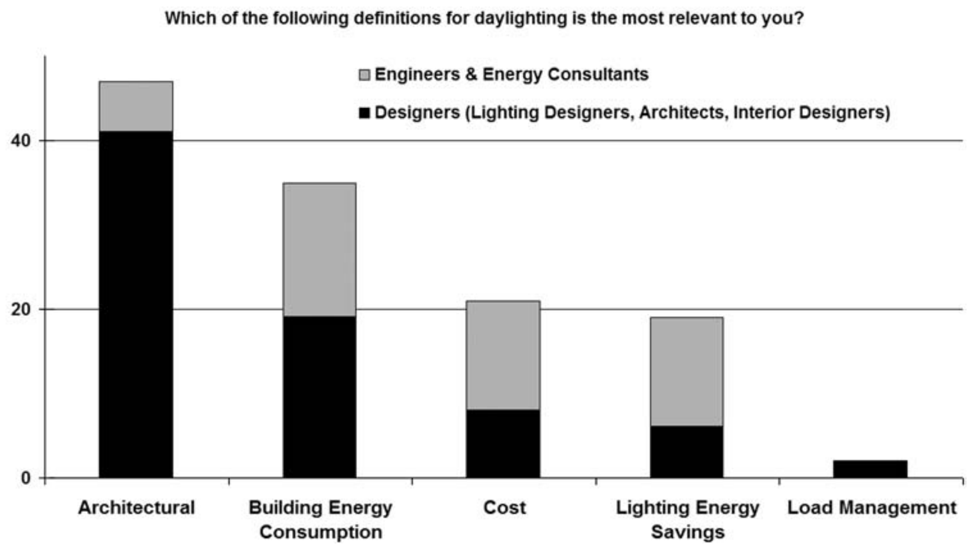


Fig. 1. Results of a recent survey on the role of daylighting in sustainable design (Reinhart C F and Galasiu A, 2006).

grouped by their self-reported profession. Architects, lighting and interior designers are marked in black. Engineers are marked in gray. The architectural and building energy consumption definitions received highest ratings, with designers mostly voting for the architectural definition and engineers concentrating on energy and costs. Note that over 80 percent of survey participants

2 Out of the over 170 individuals that participated in the survey only responses from the designers and engineers, the focus audience for this paper, are presented in Figure 1. Responses from researchers and manufacturers were omitted.

were either LEED accredited, on their way to being accredited, or regularly use the rating system 'as a design tool'.

While LEED was originally developed to provide a framework for assessing a building's performance, it also tends to be interpreted by design teams as a design guide. This observation provokes the question how effectively LEED, or a comparable green building rating system, can help a design team to implement *good daylighting* in the sense of the two most favored definitions from Table 1? Within LEED NC 2.2, the building energy consumption aspects of daylighting are covered through credits within the *Energy and Atmosphere* section. These credits are mostly concerned with predicted energy savings using building energy simulation. Energy savings from lighting controls such as occupancy sensors or programmable timers can be approximated through straightforward power adjustment factors whereas savings from photocell controlled dimming require an explicit daylight simulation (ASHRAE/IESNA 90.1 Standard - 2004 - Energy Standard for Buildings Except Low-Rise Residential Buildings, 2004).

Design professionals that concentrate on the architectural aspects of daylighting, that is, strive for that "interplay of natural light and building form", often rely on the daylight and views credits 8.1 and 8.2 within the LEED-NC version 2.2 *Indoor Environmental Quality* section for a performance metric (US Green Building Council 2006). The intent of these two daylighting credits is to provide "a connection between indoor spaces and the outdoors through the introduction of daylight into the regularly occupied areas of the building" (US Green Building Council 2006). The performance requirements used to meet this intent are a "glazing factor[3] above 2 percent" or "achieve a minimum illuminance level of 250 lx [25fc] on a clear equinox day at noon" in 75 percent of regularly occupied spaces (daylight credit) and to "achieve a direct line of sight between 90 percent of all regularly occupied spaces and a vision glazing" (view credit) (US Green Building Council 2006). The accompanying LEED reference guide mentions glare control as a common failure for daylighting strategies and recommends the use of shading devices to remedy these problems. However, no further guidance is provided in the reference guide and no metrics exist to quantify the effectiveness of such solar control devices. Research on occupant use of shading devices revealed that once direct sunlight is incident on a VDT surface, blinds are lowered for hours, days or even months afterwards (Rea 1984; Rubin, Collins, and Tibott 1978). Even in the case of an 'active' user, blinds remain routinely closed for hours after glare conditions have disappeared (Inoue, Kawase, Ibamoto, Takakusa, and Matsuo 1988; Rea 1984; Reinhart and Voss 2003). As a consequence, the daylighting intent is compromised, the connection to the outdoors is diminished, and the electric lighting is routinely switched on in many buildings even during daylit hours.

This paper argues that optimizing a building with respect to daylight/glazing factor and view to the outside does not necessarily promote good daylighting design but merely leads to a one-dimensional, "the more the better" design philosophy. Even if the avoidance of direct sunlight is added as an additional design criterion, some key design parameters are neglected, which puts some daylighting techniques at an arbitrary disadvantage compared to others. The paper then reviews the concept of dynamic performance metrics that capture the site-specific, dynamic interaction between a building, its occupants, and the surrounding climate on an annual basis as an alternative design approach. To

3 The formulae used to calculate the 'glazing factor' in LEED 2.2 correspond to those used in LEED 2.1 to calculate the 'daylight factor'.

further illustrate the predictive power of dynamic performance metrics, several previously suggested metrics are applied to a series of example offices. An outlook of how dynamic performance metrics could be introduced into green building rating schemes is given in the discussion.

2 CURRENT METRICS: DAYLIGHT FACTOR, VIEW, AND THE AVOIDANCE OF DIRECT SUNLIGHT

Daylight factor, view to the outside, and (sometimes) the avoidance of direct sunlight are currently the sole quantitative performance metrics used to implement daylighting in a building. How well does the use of these measures lead to good daylighting design according to the architectural definition in Table 1?

2.1 DAYLIGHTING FACTOR

The daylight factor is defined as the ratio of the internal illuminance at a point in a building to the unshaded, external horizontal illuminance under a CIE overcast sky (Moon and Spencer 1942). The concept of using an illuminance ratio to quantify the amount of daylight in buildings has at least been around since 1909 when Waldram published a measurement technique based on the approach (Waldram 1909). The original motive for using ratios rather than absolute values was to avoid the difficulty of having to deal with "frequent and often severe fluctuations in the intensity of daylight" (Waldram 1950). Initially, *sky factors* were used that quantify the contribution of direct light from the sky dome to a point in a building. Over time the sky factor evolved into the daylight factor, as light reflected from external obstructions, light losses through glazings, and internal reflectances were added as well (Waldram 1950). In 1949 the reference sky changed from a uniform to what is now a CIE overcast sky (Moon and Spencer 1942).

In those early days, illuminance ratios were primarily used as legal evidence in court. In Waldram's words, "legal rights of light . . . constituted practically the only profitable . . . field for daylight experts" (Waldram 1950). Based on an old Roman law, the UK Prescription Act of 1832 established that if one has benefited from daylight access across someone else's property for over 20 years, 'an absolute and indefensible rights to light' is granted to the window. A violation of a window's right to light was found when a new neighboring structure caused 'inadequate' indoor daylight levels (Waldram 1950). The decisive question has of course always been what one might consider to be adequate daylighting levels for various tasks. Nowadays 500 lx on the work plane are often recommended for office work (Canadian Labor Code, Part II: Occupational Safety & Health 1991; IESNA Lighting Handbook (9th Edition) 2000). Assuming an outside illuminance of around 10000 lx under an overcast sky, the corresponding daylight factor requirement becomes 500 lx/10000 lx = 2 percent, which happens to coincide with the LEED threshold level.

This brief historical excursion suggests that the daylight factor was never meant to be a measure of good daylighting design but a minimum legal lighting requirement. Given this background, designers' expectations that it might help them to "provide a visually stimulating, healthful, and productive interior environment" seem unfounded.

Nevertheless, daylight factor remains the most widely used performance measure for daylighting and for the majority of practitioners, the consideration of any quantitative measure of daylight begins and ends with daylight factor (Nabil and Mardaljevic 2005). Over the past fifty years, this design practice has remained largely unchallenged with a few notable exceptions (Kendrick and Skinner 1980; Tregenza 1980). Its popularity probably stems from the fact that daylight factor remains the *only* widely accepted, quantitative performance measure for daylighting. There are also a number of qualities that support daylight factor's use as a design metric.

Daylight factors vary for different building designs and accordingly have the capacity to influence design choices. What design aspects are affected by the daylight factor? Building geometry, surrounding landscape and buildings, as well as surface properties (color, diffuseness, specularity, transmittance, reflectance) have an impact on the daylight factor. A common argument used by proponents of the daylight factor is that the reference overcast sky is the worst case sky condition and therefore any other sky will lead to more daylight in the space. The argument continues that movable shading devices – such as venetian blinds – are operated by occupants to avoid glare but – even if lowered – usually provide sufficient daylight to avoid electric lighting. Note that the daylight factor calculations do not include any movable shading devices as they are not needed under the worst case overcast sky condition.

On a practical level, daylight factor has the advantage that predictions are intuitive and easy to communicate within a design team. A number of calculation methods exist for the daylight factor ranging from simple spreadsheet calculations (Canadian Green Building Council 2004) to the BRE split flux method to advanced calculation techniques based on radiosity (Lighting Analysts Inc. 2006), Lumen Designer (Lighting Technologies Inc. 2006) and/or raytracing (Ward and Shakespeare 1998). Using Radiance, one can calculate daylight factor distributions for more or less any building geometry and many material types.

What "message" does daylight factor convey to its users, that is, how does the "daylight factor mindset" influence the practice of daylighting design and evaluation? Some form-giving features that are generally associated with good daylighting are indeed promoted by daylight factor: high window-head heights, high reflective ceiling and wall finishes, narrow floor plans, large facade and skylight openings with high transmittance glazings. A daylight factor optimized building admits as much daylight as possible into the building, following a "the more the better" approach. Taking this to the extreme, *the daylight factor optimized building has a fully glazed building envelope.* Commercial buildings with fully glazed facades often exhibit comfort and energy problems, revealing that the above sketched argument for the use of daylight factor is flawed.

What are the limitations of the daylight factor metric? Design recommendations based on the daylight factor are the same for all facade orientations and building locations as the daylight factor does not consider season, time of day, direct solar ingress, variable sky conditions, building orientation, or building location. This bears a number of important consequences: Daylight factor investigations cannot help to develop glare prevention strategies for different facade orientations, even though problems of glare associated with low solar altitudes are known to be most prominent for east and west facing facades and can be significant. Daylight factor analysis cannot even provide a warning flag as to whether there will be a glare problem in certain parts of a building.

2.2 VIEW TO THE OUTSIDE

The provision of a view to the outside is promoted in buildings through the LEED rating system. The system stipulates that 90 percent of regularly occupied spaces should have a direct line of sight to the outside through a vertical window that is located between 2′6″ (76 cm) and 7′6″ (228 cm) above the floor. This credit aims to acknowledge findings that a view to the outside is a highly praised benefit of a window. As it stands, the design criteria has several shortcomings, the most important one being that research has shown that to qualify as a “view”, a visual connection to the outside from a point in a building has to extend above a minimum solid angle width *and* height, the size of which depends on the type of view (Farley 2001; Ne’eman and Hopkinson 1970). View benefits are also dependent on the content of the view (Ne’eman and Hopkinson 1970). The LEED criteria become less meaningful for spaces in which a movable shading device attached to a view window is frequently fully lowered due to glare. Perforated roller shades or horizontal venetian blinds with the slats set in horizontal position can mitigate this effect by still allowing some view to the outside.

2.3 DAYLIGHT FACTOR AND AVOIDANCE-OF-DIRECT-SUNLIGHT

Fortunately, many design teams are aware of the above cited limitations of the daylight factor and consider the avoidance of direct sunlight in parallel with daylight factor predictions. Direct sunlight studies can be performed using simulations or scale model measurements. The objective is to design facades that avoid direct sunlight in the building during the cooling season. A consequent combination of daylight factor predictions and direct shading studies leads to a building in which facade openings are reduced to the minimum possible size and a required minimum daylight factor can be maintained within a desired area adjacent to facade and ceiling openings. It is interesting to note that in combination with a direct shading analysis, the daylight factor is reduced to its initial historic scope: A minimum level of interior daylight by which the users can ‘get by’. Buildings that are the result of this “combined approach” (weighting daylight factor against unwanted solar gains) should exhibit a considerably better energy balance than those designed following a daylight-factor-only approach. A remaining, valid question is: “Could it be better?”

A practical limitation of the combined approach is that only static shading devices such as lightshelves can be considered, whereas the performance of dynamic shading devices such as venetian blinds remains elusive. It remains therefore difficult to compare the performance of a lightshelf or a translucent glazing to arguably the most common solution for sidelit spaces: A window with manually operated venetian blinds.

Also, even though the combined approach considers building orientation and latitude, the actual climate in which the building is placed is not considered. A building in Vancouver, Canada, (latitude 49° N), a climate renowned for its rainy winters, is treated the same as a building in Regina, Canada, (latitude 50° N), a climate characterized through clear winter days with a snow covered ground for several months of the year.

Finally, the combined approach completely ignores building type and occupant requirements of the building. Is it a school that is occupied half days from September to June or a hospital with 24/7 service? What lighting levels are required by the occupants?

3 DYNAMIC DAYLIGHT PERFORMANCE METRICS

This section describes dynamic daylight performance metrics as an alternative to the daylight factor-based approaches described in the previous section.

3.1 TODAY'S DESIGN CONTEXT

Dynamic performance metrics require the use of three-dimensional CAD software as well as a daylight simulation model. A series of circumstances have recently lead to an increased use of daylight simulation tools in professional practice and at some schools of architecture:

- *Access* to enhanced computing power at affordable prices for small to medium-sized Architectural and Engineering firms and architectural students.
- *Widespread computer agility and interest* in information technology and multimedia within the current generation of graduating architects. Consider the following numbers: A 1990 survey of the US architectural community found that over 75 percent of participants “could not name a CAD system they had used in the past” (Hattrup 1990). A 1997 study concluded that “90 percent of design professionals [surveyed] use some kind of CAD tool in their commercial design work” (Turnbull and Loisos 2000). Today, architecture students throughout North America are required to learn at least one three-dimensional CAD tool. Many acquire proficiency in several tools.
- *Availability* of enhanced user interfaces that allow users to generate three-dimensional building models, carry out a daylight simulation, and display the results in a meaningful, easy-to-understand fashion. The authors' teaching experiences suggest that architectural students are now able to carry out advanced daylighting studies after only a few weeks of formal instruction[4].

While most current daylight simulation tools remain limited to daylight factor and illuminance calculations and/or shading analysis studies, a few offer the capability to carry out annual calculations. The following section discusses the extra effort required by the simulationist to go from a daylight factor analysis to a dynamic daylight simulation.

3.2 DYNAMIC DAYLIGHT SIMULATIONS

Dynamic daylight performance metrics are based on time series of illuminances or luminances within a building. These time series usually extend over the whole calendar year and are based on external, annual solar radiation data for the building site. The key advantage of dynamic daylight performance metrics compared to static metrics is that they consider the quantity and character of daily and seasonal variations of daylight for a given building site together with irregular meteorological events.

Several studies have demonstrated that the Radiance raytracer combined with a daylight coefficient approach and the Perez Sky Model is able to reliably and effectively calculate time series of illuminances and luminances in buildings (Mardaljevic 2000; Reinhart and Andersen 2006; Reinhart and Walkenhorst 2001). An overview of the daylight coefficient approach and selected Radiance validation studies can be found under Reinhart and Anderson (Reinhart and Andersen 2006). Table 2 lists several Radiance-based daylighting tools that can be used to carry out dynamic daylight simulations.

4 See e.g.: *http://www.arch.mcgill.ca/prof/reinhart/arch474/winter2005/* (last accessed Feb 2006)

TABLE 2.
Overview of dynamic daylight simulation Programs

Program	Simulation Engine	Dynamic Simulation Algorithm	Web Sites (Last Accessed Mar 2006)
Adeline	Radiance	statistical sky	*www.ibp.fhg.de/wt/adeline/*
Daysim#)	Radiance	daylight coefficients & Perez	*www.daysim.com*
ESP-r	Radiance	daylight coefficients & Perez	*www.esru.strath.ac.uk/Programs/ESP-r.htm*
Lightswitch Wizard#)	Radiance	daylight coefficients & Perez	*www.buildwiz.com*
SPOT (>ver 4.0)#)	Radiance	Annual CIE sky simulation	*www.archenergy.com/SPOT*

#)Uses the validated Daysim method which is based on a modified version of the Radiance program “rtrace”.

Using Radiance, the workflow to carry out a dynamic daylight simulation is largely identical to the one for a daylight factor calculation. Most of the preparation time usually goes into the preparation of the three-dimensional CAD model, the specification of optical surface properties both within and outside of the building, and the specification of sensor points within the building.

For a dynamic simulation, an annual climate file for the building has to be imported that includes hourly data of direct and diffuse irradiances. The US Department of Energy EnergyPlus site offers climate data for hundreds of sites worldwide free of charge (Crawley, Hand, and Lawrie 1999)[5]. If one wants to decrease the time interval of the annual time series from hours to minutes a validated, stochastic model (Olseth and Skartveit 1989; Walkenhorst, Luther, Reinhart, and Timmer 2002) is available within the Daysim tool to do so. The use of the model is fully automated and largely hidden from the simulationist.

Dynamic daylight simulations involve (a) a pre-processing step during which a set of daylight coefficients is calculated for each sensor point and (b) a post-processing step during which the daylight coefficients are coupled with the climate data to yield the annual time series of interior illuminances and luminances. Both steps are fully automated within the above mentioned programs[6]. In the case of Daysim, calculation times are roughly eight times longer for dynamic compared to static simulations. At current processor speeds (~4GHz), a dynamic simulation of a regular rectangular room runs for about 20 minutes. For a larger building with several hundred sensor points, the simulation time increases[7].

It should be noted that instead of using computer simulation software, a new ‘single-patch’ sky simulator has been recently proposed to measure daylight coefficients in scale models (Bodart, Deneyer, De Herde, and Wouters 2006). The resulting sets of daylight coefficients can, in principal, be further processed using the same analysis software as for Radiance-based dynamic daylight simulations (Bodart and others 2006). While the use of scale model based dynamic simulations could effectively promote the use of dynamic metrics in schools of architecture (major producers of scale models) particular attention

5 *http://www.eere.energy.gov/buildings/energyplus/cfm/weatherdata.cfm* (last accessed Feb 2006)

6 ADELINE uses the concept of the statistical sky (Szerman M, 1996) instead of daylight coefficients.

7 Architectural and Engineering Firms who specialize in daylight simulations often invest in a dedicated set of “number crunching” computers to avoid disruption of their regular work flow.

has to be paid to intrinsic limitations of physical model studies such as parallax errors (Mardaljevic 2002).

3.3 A REVIEW OF DYNAMIC DAYLIGHT PERFORMANCE METRICS

The preceding section made the case that the extra effort to carry out a dynamic as opposed to a static daylight simulation has been reduced recently, making the resulting annual time series of interior illuminances or luminances more readily available to nonexpert designers. The obvious question is what a designer is to do with the voluminous data from a climate-based analysis (thousands of data points for each sensor). The task at hand is to reduce the data without diminishing its value for building design. This section provides a systematic review of the choices that need to be made to develop a dynamic performance metric for a space.

3.3.1 IDENTIFYING SENSOR POINTS

The first performance-metric-related decision a simulationist faces is to pick the number and location of sensor points. A common approach is to define a grid of upward facing illuminance sensors that extends throughout a lighting zone. A typical grid resolution would be 0.5 m × 0.5 m at work plane height (0.8m above the floor). Depending on the particular space, some of these sensors might be singled out as 'core work plane sensors', that is, sensors close to where the occupants are usually located (Nabil A and Mardaljevic J, 2005). The choice of using illuminance as opposed to luminance sensors is linked to the decision under 3.3.3 to use work plane illuminances as a basis to judge whether the daylighting in a space is 'adequate'. If other criteria such as luminance ratios in the field of view (FOV) were chosen under 3.3.3, the choice of sensor location and type would have to be adopted accordingly.

3.3.2 DEFINING A TIME BASIS

The next step is to decide which times of the year to consider as a time basis for daylight performance metrics. Two obvious time selection criteria come to mind: (a) the daylit hours during the year or (b) the occupied times of the year for any given zone in the building. Both approaches have their pros and cons.

An initial reaction of a designer might be to use the daylit hours during the year since these hours are unambiguously intertwined with the building site. Building occupancy patterns are not standard architectural considerations when determining building form. Also, building usage might change over time as warehouses become offices and offices become apartments. If one is to design a truly sustainable building with a long term perspective, the annual daylit hours will never change unless the surrounding urban environment changes.

On the other hand, occupancy patterns and occupants' lighting requirements lie at the heart of the desired interplay between natural light and building form (Table 1). Daylighting needs "witnesses" to be appreciated and these witnesses will rely on a set of cultural and practical expectations when judging a space. The admittance of bright sunlight might be evaluated positively on a winter day in an atrium, cafeteria, and so on but less so at a VDT work space. Based on this argument, the authors recommend using occupancy profiles as the time basis for dynamic daylight performance metrics.

This time basis has the advantage that the resulting metrics are normalized: a "perfectly daylit" building that satisfies the daylighting requirement (defined under 3.3.3) throughout the occupied times of the year will score 100 percent. In contrast, a zone occupied only outside of daylit hours will, rightfully, score 0 percent. Also, as a counterpoint to the above argument for using all daylight hours, when a building function changes (that is, a warehouse becomes an apartment) many times apertures are added or removed as part of the retrofit.

A critical reader might object that - in terms of practicality - the task of assigning occupancy patterns for various building zones might be onerous for the design team and ambiguous if the performance metric is to be used in rating schemes. A contra-argument is that typical occupant profiles are already routinely used in energy performance simulation and standards exist for a range of building zones and types (National Research Council Canada 1997).

3.3.3 DAYLIGHTING REQUIREMENTS

Once sensor locations and a time basis have been established, the next step is to choose a criteria that determines whether the daylight situation at a sensor is '*adequate*' at a particular point in time. Several criteria have been suggested in the past:

- *Daylight Autonomy (DA)*, uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that an occupant can work by daylight alone. Required minimum illuminance levels for different space types can be directly taken from reference documents such as the IESNA Lighting Handbook (IESNA Lighting Handbook (9th Edition), 2000). The definition of daylight autonomy being 'the percentage of the year when a minimum illuminance threshold is met by daylit alone' goes at least as far back as 1989 when it was mentioned in a Swiss norm (Association Suisse des Electriciens 1989). According to that norm, the term is a function of daylight factor and minimum required illuminance level. In 2001 Reinhart and Walkenhorst redefined daylight autonomy at a sensor as the percentage of the *occupied* times of the year when the minimum illuminance requirement at the sensor is met by daylight alone (Reinhart and Walkenhorst 2001). In later publications, the concept of daylight autonomy was further refined by combining it with a manual blind control model that predicts the status of movable shading devices at all time steps in the year. The resulting concept of an 'effective' daylight autonomy was applied to open plan and private offices (Reinhart 2002; Reinhart and Andersen 2006).
- *Useful Daylight Illuminances (UDI)*, proposed by Mardaljevic and Nabil in 2005, is a dynamic daylight performance measure that is also based on work plane illuminances (Nabil and Mardaljevic 2005; Nabil and Mardaljevic 2006). As its name suggests, it aims to determine when daylight levels are 'useful' for the occupant, that is, neither too dark (<100 lx) nor too bright (>2000 lx). The upper threshold is meant to detect times when an oversupply of daylight might lead to visual and/or thermal discomfort. The suggested range is founded on reported occupant preferences in daylit offices (Nabil and Mardaljevic 2005). Based on the upper and lower thresholds of 2000 lx and 100 lx, UDI results in three metrics, that is, the percentages of the occupied times of the year when the UDI was achieved (100–2000 lx), fell-short (<100 lx), or was exceeded (> 2000 lx). The last bin is meant to detect the likely appearance of glare.
- *Continuous Daylight Autonomy (DA_{con})*, recently proposed by Rogers, is another set of metrics that resulted from research on classrooms (Rogers Z, 2006). In contrast to earlier definitions of daylight autonomy, partial credit is attributed to time steps when the daylight illuminance lies below the minimum

illuminance level. For example, in the case where 500 lx are required and 400 lx are provided by daylight at a given time step, a partial credit of 400 lx/500 lx = 0.8 is given for that time step. The result is that instead of a hard threshold the transition between compliance and noncompliance becomes softened. This change to the metric can be justified by field studies that indicate that illumination preferences vary between individuals (Jennings, Rubinstein, DiBartolomeo, and Blanc 1999; Reinhart and Voss 2003) and that many office occupants tend to work at lower daylight levels than the commonly referred 300 or 500 lx (Lindelöf and Morel 2006; Reinhart and Voss 2003). Essentially, the metric acknowledges that even a partial contribution of daylight to illuminate a space is still beneficial.

To synchronously consider the likely appearance of glare, a second quantity, maximum Daylight Autonomy (DA_{max}), is reported together with DA_{con} to indicate the percentage of the occupied hours when direct sunlight or exceedingly high daylight conditions are present. Assuming that the threshold of potentially glary conditions depends on the space type, DA_{max} was defined to be a sliding level equal to ten times the design illuminance of a space. E.g. for a computer lab with a design illuminance of 150 lx DA_{max} corresponds to 1500 lx (Rogers 2006). This upper threshold criteria is essentially a measure of the occurrence of direct sunlight or other potentially glary conditions and can give an indication of how often and where large illuminance contrasts appear in a space.

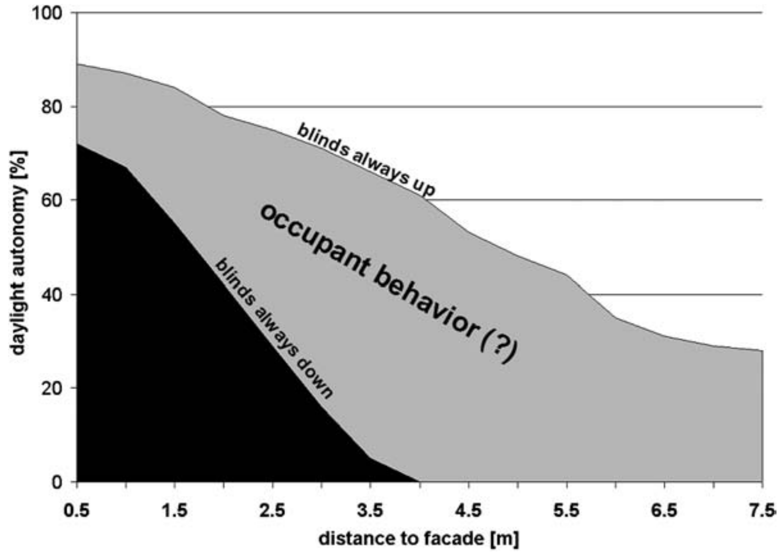
- *Annual Light Exposure* is an already established performance indicator to design spaces that contain light-sensitive artwork. It is defined as the cumulative amount of visible light incident on a point of interest over the course of a year. Annual light exposure is measured in lux hours per year. The International Commission on Illumination (CIE) Division 3 TC3.22 'Museum lighting and protection against radiation damage' recommends annual light exposures for various types of artwork ranging from stone and ceramics to silk and sensitive pigments (International Commission on Illumination (CIE) Division 3 TC-22, 2004). Dynamic daylight simulations have already been used to establish that recommended annual light exposure levels in a museum are met (Franks 2006). The time basis for this metric is 'permanent occupancy', that is, 24 hours a day, 365 days a year, as light sensitive materials are always at risk of radiation damage.

3.3.4 SHADING DEVICES (STATIC AND MOVABLE)

According to a recent survey on the use of daylight simulations during building design, shading type and control were the most common design aspects influenced by a daylighting analysis (Reinhart and Fitz 2006). This is not surprising given that the shading device choice decisively defines the amount of daylight available in a space.

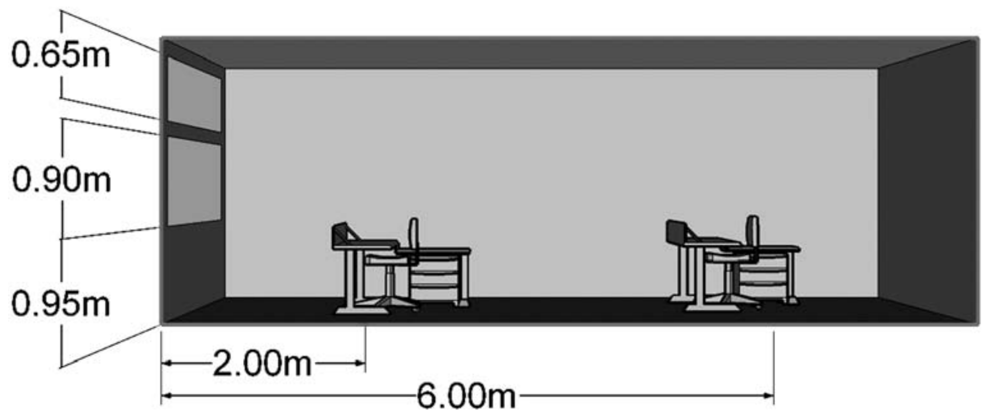
In the context of a dynamic daylight simulation, shading and light redirecting devices can be classified into either static (for example, a lightshelf, an overhang, or a laser cut panel) or movable (for example, venetian blinds, roller blinds, or curtains). In the former case, the shading device can simply be modeled as part of the building and does not require any further attention as far as the simulation is concerned. In the latter case, annual illuminance profiles for at least two shading device settings, for example, blinds up and down, have to be calculated. In this case, the control mode for the movable shading device has a decisive impact on the 'effective' available daylight in a space as shown in Figure 2.

Fig. 2. Daylight autonomy distribution in an office for two extreme blind usage patterns.



The figure presents conventional daylight autonomy distributions for an office facing south located in Vancouver, Canada. Office dimensions are shown in Fig. 3. Office hours are 8 AM to 5 PM, Monday to Friday, and the minimum

Fig. 3. Side view of the office investigated in Fig. 2.



illuminance level is 500 lx. No surrounding buildings are considered in the simulation. The upper edge of the gray area in Fig. 2 indicates the daylight autonomy in the space if the venetian blinds are retracted all year long. The border between the gray and black areas shows the daylight autonomy if the blinds are lowered all year with a slat angle facing about 40° towards the ground. The lower edge of the black area corresponds to a scenario in which the blinds are fully closed all year. One would expect 'actual' daylight autonomies to lie somewhere within the gray area. Fig. 2 clearly shows how strong the annual daylight availability in a sidelit space depends on how the occupant operates the shading device. It makes a compelling case that the use of shading devices should be considered in a daylighting metric.

How can this be accomplished? Movable shading devices can be operated either manually, automatically, or via a combination of both. Automatic control, typically based on a photocell and/or occupancy sensor, is relatively straightforward to model if the control algorithm is known. In the case of manually operated blinds, the simulation has to mimic how an occupant might operate the blinds. The *Lightswitch* algorithm is an example 'user behavior model' that is exclusively based on field data (Reinhart 2004). To use the model, each movable shading device has to be associated with one or several work plane sensors that characterize the area where the individual(s) controlling the shading device is (are) usually located. The illuminances at these work plane sensors control the setting of the shading device. Lightswitch recognizes two distinct types of occupant behavior. For an *active* user, the blinds are opened once in the morning upon arrival and closed if the space is occupied and direct sunlight above $50Wm^{-2}$ is incident on any of the work plane sensors. For a *passive* user the blinds remain lowered throughout the year. The resulting daylight autonomy for a passive user is the transition between the gray and the black area in Fig. 2. The use of a user behavior model allows the meaningful comparison of daylighting strategies involving manually controlled venetian blinds – arguably the most common shading device currently used in North America and Europe – and more advanced daylighting strategies involving static and dynamic shading devices.

3.3.5 SPATIAL CONSIDERATIONS

Introducing movable shading devices effectively couples all sensors in a lighting zone together. While only the work plane sensors or the photocell *determine* the status of the venetian blinds at any given point in time, all other sensors in the lighting zone are *affected* by the resulting shading device setting. For example, in the deep plan, sidelit office in Fig. 3, the occupant near the window drives the setting of the blinds, which may lead at times to less daylight than desirable for the occupant sitting further back in the room.

In cases where a space features several independently operated movable shading devices, the number of combinations of different shading devices settings rises exponentially. At the same time, the dynamics between different users within such a space becomes increasingly complicated. Such a situation cannot be addressed by the current generation of user behavior models.

3.3.6 IDENTIFYING A SINGLE METRIC FOR A SPACE

Once a dynamic daylight performance metric has been calculated for multiple sensor points in a space, the result can be presented through graphical representations such as contour plots and falsecolor maps. Such graphical presentations are valuable by themselves because they present how daylight is distributed throughout a space. Yet, for a rating system it is often more desirable to come up with single metric for a space. For dynamic performance metrics, different overall rating procedures have been proposed in the past.

One approach is to concentrate on work plane sensors assuming that the metric near the workplace is most relevant. In Fig. 2, this would be the sensors on the center axis at 2 m and 6 m from the facade. This is the approach that has been used for the daylight autonomy calculations (Reinhart 2002).

In order to capture the interconnection between different sensors in a lighting zone, Mardaljevic recommended to group all work plane sensors together and consider daylight only "useful" if all work place sensors synchronously lie in the recommended 100 lx to 2000 lx range (Nabil and Mardaljevic 2005).

Rogers proposed to report the area percentage of a workplane with a continuous daylight autonomy (DA_{con}) level above either 40 percent, 60 percent or 80 percent. To avoid overly daylit conditions or conditions of too much direct sunlight, Rogers also reported the area percentage of a workplane in which DA_{max}, the maximum accepted illuminance, was exceeded for more than 5 percent of the time.

4 EXAMPLE APPLICATIONS

This section presents a series of example applications of the previously discussed static and dynamic metrics in a two-person office. The intent of this section is to demonstrate how the results of a daylighting analysis differ depending on the daylight performance metric used.

The reference geometry corresponds to the deep plan office in Fig. 3 (4m high, 4m wide, and 8m deep). The material properties of individual surfaces are shown in Table 3. By default, the office is located in Boulder, Colorado, USA (40° N, 105°

TABLE 3.
Material Properties of the Investigated Offices

Building Element	Material Description
Ceiling	80% diffuse reflectance
Walls	60% diffuse reflectance
Floor	30% diffuse reflectance
Mullions	50% diffuse reflectance
Lightshelf	85% diffuse reflectance
Overhang	75% diffuse reflectance
View window	40% visual transmittance
Daylight window*	60% visual transmittance
Venetian blinds	either fully retracted or fully lowered with a slat angle of 40° facing downwards, the slats have a diffuse reflectance of 50%
Translucent panel	ideal diffuser with a diffuse-diffuse transmittance of 16% (Reinhart C F & Andersen M, 2006)
External ground	25% diffuse reflectance

*When facing north or in combination with a lightshelf, the transmittance of the daylight window was 70%.

W), faces South, and is used as a regular office space with a design illuminance of 400 lx and occupancy Monday through Friday from 8AM to 5PM.

Four different facade layouts were considered which are shown in Fig. 4. For the *Lightshelf* variant, the upper daylighting window was adorned with an overhang (depth 0.6 m) and an internal lightshelf (depth 0.9m).[8] For the *Translucent* variant, the upper daylighting window was replaced with a translucent panel with a diffuse-diffuse transmittance of 16 percent. Finally, for the *Punched* variant, the width of the windows was reduced from 3.4m to 2m.

Other design parameters that were modified were building location, facade orientation, occupancy pattern, and design illuminance.

4.1 METHODOLOGY

For all investigated design variants, daylight factor (DF), conventional daylight autonomy (DA), continuous daylight autonomy (DA_{con}), and Useful Daylight Index (UDI) were calculated as described in the following.

8 A solar shading analysis was carried out to determine the optimal depth for the overhang and lightshelf for Boulder assuming a cooling period from March 21st to September 21st. The size of the overhang is such that on March 21st at noon, the overhang fully shades the daylight window. The size of the internal lightshelf is set so that on December 21st at noon no direct sunlight through the daylight window is incident onto the floor.

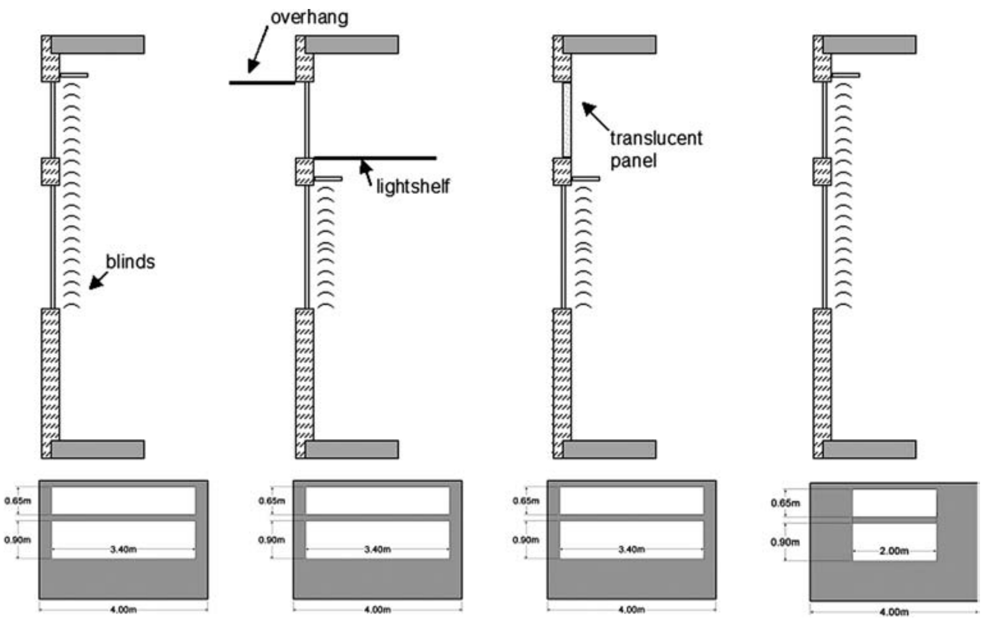


Fig. 4. Investigated facade alternatives.

For all performance metrics, the same annual illuminance profiles were used based on Daysim calculations. The simulation time step was one hour. Nondefault Radiance simulation parameters are listed in Table 4. Venetian blinds were

TABLE 4. Utilized Radiance Simulation Parameters

Ambient Bounces	Ambient Division	Ambient Sampling	Ambient Accuracy	Ambient Resolution	Direct Threshold	Direct Sampling
5	1512	20	0.1	300	0	0

operated in either one of three modes: *Active* or *passive* user (see section 3.3.4) or *automated*. In automated mode, the blinds remained closed only when direct sunlight was incident on either of the two seating positions. The mode corresponds to an idealized automated control and is supposed to indicate if and by how much the daylight performance for an automated control changes compared to the two manual controls.

Daylight factors and conventional daylight autonomies were calculated on the center line at distances of 2 m and 6 m from the facade. These sensors correspond to the seating positions of the two occupants in the front and the back of the office (Fig. 3). Continuous daylight autonomy calculations were based on a 0.5 × 0.5 m grid that extended across the whole office. Useful daylight index calculations were based on the same grid but reported separately for the front and the back half of the space, that is, $UDI_{100-2000}$ was only met if all sensors in the front or back half lay between 100 lx and 2000 lx.

4.2 SIMULATION RESULTS

4.2.1 FAÇADE LAYOUT

For variants 1a to 1 day, the reference office was combined with the four different facade variants from Fig. 4 (see Table 5). Results for the different performance metrics are shown in Table 6. Table 7 shows the ratings of the four design variants according to the different metrics. When a metric led to different ratings

TABLE 5.
Description of Variants 1a to 1d

Variant	Climate	Facade	Or.	Shade Control	Space Use
1a	Boulder, CO	Reference	South	Manual (active user)	typical office
1b	Boulder, CO	Lightshelf	South	Manual (active user)	typical office
1c	Boulder, CO	Translucent	South	Manual (active user)	typical office
1d	Boulder, CO	Punched Windows	South	Manual (active user)	typical office

TABLE 6.
Simulation Results for Variants 1a to 1d

Variant		1a		1b		1c		1d	
Façade		Reference		Lightshelf		Translucent		Punched	
% of Time When the Blinds are Down		54%		45%		45%		53%	
Work Place (front/back)		f	b	f	b	f	b	f	b
Daylight Factor (DF)		3.5%	0.6%	1.9%	0.4%	2.2%	0.4%	1.3%	0.2%
Daylight Autonomy (DA)		76%	1%	90%	10%	86%	0%	29%	0%
Continuous DA (DA_{con})	>40%	71%		100%		76%		38%	
	>60%	52%		73%		60%		20%	
	>80%	34%		54%		41%		8%	
Maximum DA (DA_{max})	>5%	6%		8%		5%		0%	
$UDI_{<100}$		16%	60%	6%	20%	9%	42%	65%	97%
$UDI_{100\text{-}2000}$		52%	40%	46%	80%	47%	58%	13%	3%
$UDI_{>2000}$		32%	0%	48%	0%	44%	0%	22%	0%

TABLE 7.
Rating of Variants 1a to 1d Based on Table 6

Metric	1st Place	2nd Place	3rd Place	4th Place
Daylight Factor	Reference	Translucent	Lightshelf	Punched Window
DA	Lightshelf	Translucent	Reference	Punched Window
DA_{con}	Lightshelf	Translucent	Reference	Punched Window
UDI	Lightshelf	Translucent	Reference	Punched Window

for the front and the back of the space, the mean results for both work places were compared. Specifically, $UDI_{100-2000}$ yielded higher levels for the front work place for *Reference* than for *Lightshelf* and vice versa for the back work place. Using the mean for both results, (52 percent + 40 percent)/2 and (46 percent+80 percent)/2 yields a score of 46 percent for *Reference* and 63 percent for *Lightshelf.*

As one would expect, the results differ for the different performance metrics. *Punched* Window scored considerably lower than the other three facades in all four metrics, indicating that the illuminance level reached through the narrow window are insufficient, particularly in the back of the office.

According to the daylight factor metric, *Reference* is superior to the three other variants followed by *Lightshelf* and *Translucent*. The three dynamic metrics all rate *Lightshelf* and *Translucent* above *Reference*. DF does not take blind use into account which explains why the facade with the largest glazing area receives the highest rating. All three dynamic metrics consider blinds. The "% of time when the blinds are down" indicate that for *Lightshelf* and *Translucent*, the blinds are lowered 45 percent of the working year whereas they are closed for 54 percent or 53 percent of the working year for *Reference* or *Punched*. The reason why the blinds are closed more regularly for *Reference* than for *Lightshelf* and *Translucent* is that direct sun through the upper daylight window is never blocked or redirected. One might expect the blinds to be open more often for *Punched* since the window is smaller. The reason for the high closing rate of 53 percent for *Punched* is that the front work place, located centrally behind the window, is not effectively shielded from direct sunlight unless the blinds are drawn.

An advantage of *Lightshelf* and *Translucent* is that even when the blinds are drawn for the view window, the upper daylighting opening still admits daylight into the back of the space. The $UDI_{100-2000}$ metric shows that the lightshelf effectively doubles the useful daylight for the back work place compared to the reference case. On the other hand, a $UDI_{>2000}$ of 48 percent and DA_{max} of 8 percent suggest that the front workplace for *Lightshelf* is over-daylit. This result is somewhat misleading as only two blind settings were considered: fully opened and fully lowered with a slat angle of 40° facing downward. A 'real user' experiencing too much light could further close the Venetian blinds if desired. This, of course, would in turn lead to less daylight in the space.

DA_{con}(>60 percent) reveals that the first three facade variants light the space more evenly than the *Punched* variant with more than half of the space having continuous daylight autonomies over 60 percent compared to only 20 percent of the space for *Punched*.

4.2.2 FAÇADE ORIENTATION AND SHADE CONTROL

Variants 2a to 2c (Tables 8 to 10) show the impact of the type of shading control used on the four metrics. A comparison of variants 1b and 2a shows the effect of different facade orientations (south and east).

TABLE 8.
Description of Variants 2a to 2c

Variant	Climate	Facade	Or.	Shade Control	Space Use
2a	Boulder, CO	Lightshelf	East	Manual (active user)	typical office
2b	Boulder, CO	Lightshelf	East	Manual (passive user)	typical office
2c	Boulder, CO	Lightshelf	East	Automated	typical office

TABLE 9.
Simulation Results for Variants 2a to 2c

Variant		2a		2b		2c	
Shade Control		Manual Active		Manual Passive		Automated	
% of the Time When the Blinds are Down		84%		100%		20%	
Work Place (front/back)		f	b	f	b	f	b
Daylight Factor (DF)		1.9%	0.4%	1.9%	0.4%	1.9%	0.4%
Daylight Autonomy (DA)		68%	4%	62%	4%	86%	4%
Continuous DA (DA_{con})	>40%	75%		72%		84%	
	>60%	53%		52%		64%	
	>80%	31%		26%		46%	
Maximum DA (DA_{max})	>5%	0%		0%		4%	
$UDI_{<100}$		11%	60%	12%	67%	7%	27%
$UDI_{100-2000}$		78%	38%	83%	31%	64%	71%
$UDI_{>2000}$		12%	2%	5%	2%	29%	2%

Neither facade orientation nor shading control influence the daylight factor, the metric is identical for all these variants. In the presence of a lightshelf, both DA and DA_{con} predict that a south facade is superior to an east facade particularly in the back of the space with DA rising from 4 percent to 10 percent and DA_{con}(>60 percent) rising from 53 percent to 73 percent. This prediction is consistent with the notion that a lightshelf redirects direct sunlight of sufficient

TABLE 10.
Rating of Variants 2a to 2c Based on Table 9

Metric	1st Place	2nd Place	3rd Place
Daylight Factor	—	—	—
DA	automated	manual active	manual passive
DA_{con}	automated*	manual active	manual passive
UDI	automated*	manual active	manual passive

*DA_{max} and $UDI_{>2000}$ values indicate a greater occurrence of high daylight levels under automatic control.

altitude deeper into the space, resulting in a more uniform illumination[9]. $UDI_{100–2000}$ also clearly favors the south-facing over the east-facing lightshelf for the back work place. On the other hand, $UDI_{>2000}$ falls from 48 percent to 12 percent for the east-facing facade suggesting that it is less prone to glare. Again, this result is an artifact of the manual blind control model since the slats could be closed further. The results for the two facade orientations reveal both the challenges as well as the potential benefits of a lightshelf.

The rating between the three shading control modes is easier to interpret using all the dynamic metrics except DF which is identical for all three. *Automated* is always rated highest followed by *manual* and *passive*. The difference between an *active* and a *passive* user is small with blinds being lowered 84 percent or 100 percent of the time, respectively, opposed to only 20 percent for *automated*. The reason for this drastic discrepancy is introduced by the *active* blind control model, as it only opens the blinds once a day in the morning and closes them as soon as direct sunlight is present. This places an inherent disadvantage on east facades compared to west facades, which only receive direct sunlight later in the day (Reinhart 2002). On the other hand, $UDI_{>2000}$ raises a warning flag that 29 percent of the time during the working year the illuminance level in the front of the room lies above 2000 lx. Thus, *automated* might at times fail to close the blinds when there may actually be too much daylight in the space.

4.2.3 CLIMATE AND OCCUPANCY

Variants 3a and 3b (Tables 11 to 13) present the reference office with a lightshelf facing east. The office is used only on weekday mornings from 7AM to 1PM. The two variants differ in that the office is either located in sunny Boulder, Colorado

TABLE 11.
Description of Variants 3a and 3b

Variant	Climate	Facade	Or.	Shade Control	Space Use
3a	Boulder, CO	Lightshelf	East	manual (active user)	typical office (occupancy only in the morning)
3b	Arcata, CA	Lightshelf	East	manual (active user)	typical office (occupancy only in the morning)

or in coastal Arcata, California, (41° N, 124° W). Both locations lie roughly at the same latitude but Boulder receives about one and a half times more annual direct solar radiation than Arcata. Since both climates have the same latitude, a solar shading analysis would yield the same lightshelf dimensions.

As for the previous example, daylight factor cannot capture the influence of climate or occupancy patterns.

What change does a morning-occupancy pattern introduce compared to a standard 9-to-5 usage (variants 2a and 3a)? Since the space is facing east, the

9 Note that in this particular case, due to the overhang, the lightshelf can only function this way when incident sunlight bypasses the overhang.

TABLE 12.
Simulation Results for Variants 3a to 3b

Variant		3a		3b	
Short Description		Boulder, CO Morning Schedule		Arcata, CA Morning Schedule	
% of the Time When the Blinds are Down		83%		50%	
Work Place (front/back)		f	b	f	b
Daylight Factor (DF)		1.9%	0.4%	1.9%	0.4%
Daylight Autonomy (DA)		89%	13%	87%	5%
Continuous DA (DA_{con})	>40%	92%		86%	
	>60%	66%		63%	
	>80%	50%		47%	
Maximum DA (DA_{max})	>5%	0%		0%	
$UDI_{<100}$		2%	40%	5%	32%
$UDI_{100\text{–}2000}$		80%	52%	65%	64%
$UDI_{>2000}$		18%	9%	30%	4%

TABLE 13.
Rating of Variants 3a to 3b Based on Table 12

Metric	1st Place	2nd Place
Daylight Factor	—	—
DA	Boulder	Arcata
DA_{con}	Boulder	Arcata
UDI	Boulder	Arcata

morning-occupancy coincides with the times when most daylight is incident on the facade. Accordingly, morning occupancy scores higher than all-day usage, demonstrating that basing a dynamic metric on the occupied hours of the year 'self-normalizes' the metric.

Differences between the metrics for the two climates are small as two confounding factors cancel each other: Boulder receives more direct solar radiation but this results in the venetian blinds being closed 83 percent of the time in Boulder as opposed to 50 percent in Arcata. DA favors Boulder for the back work place as the blinds are mostly reducing daylight levels near the facade whereas the lightshelf redirects daylight into the back of the space. $UDI_{>2000}$ warns that 9 percent of the time this redirected daylight leads to an oversupply in the back of the room for Boulder. On the other hand, the $UDI_{>2000}$ predicts that in Arcata the front work place might be overly lit 30 percent of the time, a consequence of the blinds not being lowered as often as for Boulder. DA_{con} yields more or less identical results for both locations with a slight bias towards Boulder.

It is worthwhile to note that a far as 'view to the outside' is concerned, Arcata is far more desirable than Boulder as the blinds are only closed 50 percent of the time in Arcata as opposed to 83 percent in Boulder. This shows that performance metrics for view and daylight availability can lead to conflicting results.

4.2.4 ILLUMINANCE REQUIREMENTS

Variants 4a to 4c (see Tables 14–16) show the influence of the design illuminance on the four metrics. The three variants correspond to the translucent facade facing south for a design illuminance of 150 lx, 400 lx, and 1000 lx. The corresponding space usage for the three design illuminances could be a computer lab, a regular office, and a color printing facility.

Neither daylight factor nor UDI can resolve the difference between these three variants. DA simply yields higher levels for lower design illuminances. The step

TABLE 14.
Description of Variants 4a and 4c

Variant	Climate	Facade	Or.	Shade Control	Space Use
4a	Boulder, CO	Translucent	South	Manual (active user)	typical office (computer work, min ill. 150lux)
4b	Boulder, CO	Translucent	South	Manual (active user)	typical office
4c	Boulder, CO	Translucent	South	Manual (active user)	typical office (drafting room, min ill. 1000lux)

TABLE 15.
Simulation Results for Variants 4a and 4c

Variant		4a		4b		4c	
Design Illuminance		150 lux		400 lux		1000 lux	
% of the Time When the Blinds are Down		45%		45%		45%	
Work Place (front/back)		f	b	f	b	f	b
Daylight Factor (DF)		2.2%	0.4%	2.2%	0.4%	2.2%	0.4%
Daylight Autonomy (DA)		97%	53%	86%	0%	42%	0%
Continuous DA (DA_{con})	>40%	100%		73%		43%	
	>60%	100%		60%		31%	
	>80%	77%		41%		18%	
Maximum DA (DA_{max})	>5%	24%		5%		0%	
$UDI_{<100}$		9%	42%	9%	42%	9%	42%
$UDI_{100-2000}$		47%	58%	47%	58%	47%	58%
$UDI_{>2000}$		44%	0%	44%	0%	44%	0%

TABLE 16.
Rating of Variants 4a to 4c Based on Table 14

Metric	1st Place	2nd Place	3rd Place
Daylight Factor	—	—	—
DA	150 lux	400 lux	1000 lux
DA_{con}	400 lux	150 lux	1000 lux
UDI	—	—	—

from 400 lx to 150 lx is significant (0 percent to 53 percent for the back), revealing that the illuminances in the back usually lie between 150 lx and 400 lx. DA_{con}(>60 percent) saturates for 150 lx indicating that the required illuminances are met throughout the space for at least 60 percent of the time. On the other hand, DA_{max} raises a warning flag that for the 150 lx variant nearly a quarter of the space is subject to more than 1500 lx, that is, the illuminance uniformity of the space is poor.

5 DISCUSSION AND CONCLUSION

5.1 STATIC AND DYNAMIC METRICS

The information presented throughout this document suggest that illuminance-based dynamic performance metrics such as daylight autonomy, continuous daylight autonomy, and useful daylight index have become 'viable' alternatives to the daylight factor metric. Arguments in their favor are:

(a) The underlying physical simulation models have been rigorously validated for a range of building materials and geometries.
(b) A number of design tools exist that make the required simulation capabilities accessible to nonsimulation-experts.
(c) The extra effort required on behalf of the simulationist to calculate a dynamic metric as opposed to the daylight factor is small and the additional inputs

required (climate data, occupancy patterns, space usage) are readily available.

(d) The predictive power of these metrics for design comparisons is larger than for the daylight factor.

The last argument is crucial and requires further qualification. The examples in section 4 yielded that design recommendations based on the daylight factor either contradicted the recommendations of the dynamic metrics or that the daylight factor could not resolve the difference between the variants. Just because the dynamic metrics contradicted the daylight factor rating does not necessarily mean that they are 'right'. One should rather revisit the four facades from Fig. 4 and try to understand the origin between these differences. The reference facade (favored by the daylight factor) admits the most daylight into the adjacent space. But, the blind control model predicts that the venetian blinds, which extend over the view and daylight windows, will be lowered 54 percent of the year. This will seriously reduce the amount daylight available within the space. For the *Lightshelf* and *Translucent* variants, the venetian blinds only covered the view window and the blind model predicted that they will be closed for 45 percent of the year. As a result, one would expect more daylight to be available for these variants especially in the back of the space. The better performance that the dynamic metrics attest to *Lightshelf* and *Translucent* is therefore supported by design intuition. The fact that the daylight factor fails to compare all other design variants in section 4 reiterates its limitations as a design metric.

The three dynamic metrics all have their merits and shortcomings. Daylight autonomy only relies on task-specific minimum illuminance levels which have the advantage of already being well established for different space types (IESNA Lighting Handbook (9th Edition), 2000). Combined with a manual blind control model, daylight autonomy can be used to directly compare the performance of movable and static shading devices.

Useful Daylight Illuminances require upper and lower thresholds which first have to be established for different building zones, requiring further research (see below). On the other hand, UDI provides an effective mechanism to flag the zone in a building in which a shading device is needed which makes it attractive for initial design investigations that concentrate on the daylighting/shading performance of the fixed building form. Recently it has been suggested that the UDI scheme could be enhanced by partitioning the $UDI_{100-2000}$ range into 100–500 lx and 500-2000 lx bins (Mardaljevic 2006). These bins have been provisionally called $UDI_{supplementary}$ and $UDI_{autonomous}$ for the lower and upper ranges, respectively. That is, supplementary electric lighting might be needed for daylight illuminances in the lower range, whereas daylight alone is sufficient when levels are in the higher range (Mardaljevic 2006).

Continuous daylight autonomy and DA_{max} combine elements of both earlier metrics. DA_{con} retains the concept of space–specific design illuminances but introduces partial credit for daylight contributions that lie below the design illuminance. This softens the transition between compliance and noncompliance, and acknowledges that 'some' daylight is preferable to 'no' daylight. The sliding upper threshold of ten times the design illuminance incorporates aspects of glare prevention and may detect the frequent appearance of high illuminance contrasts within a space. The custom of reporting the percentage of space area with daylight autonomies that lie above a minimum threshold resembles the LEED daylight factor criteria. A remaining weakness of the DA_{max} concept is that the constant factor of ten times the design illuminance is based on intuition rather than documented research.

The next obvious question for a practitioner is: 'which metric should I use?' Since all metrics can be automatically reported side-by-side, it seems advisable to consider them all (and others that may be developed) synchronously until a set criteria has been established as outlined in the following.

5.2 THE NEED FOR BENCHMARKS

Following the arguments presented in section 5.1, the reader may jump to the conclusion that dynamic daylight performance metrics are ready to be introduced into green building rating systems to act as alternative compliance paths to daylight factor-based criteria. In the authors' opinion, one step is still missing before this should be done. As demonstrated in section 4, dynamic performance metrics can already be successfully used for comparative studies between different design variants. What is missing are absolute benchmark levels, which establish pass/ fail criteria for dynamic performance metrics. Rather than following the LEED daylight factor approach of assigning a 2 percent minimum level in an *ad hoc* fashion, the authors advocate a more scientifically based approach. For example, selected dynamic metrics could be 'calibrated' against a series of building examples or case studies. The daylighting 'quality' of these case studies would have to be independently established beforehand through evaluations by building occupants and daylighting design experts. Being a substantial research undertaking in itself, this approach holds the promise of delivering a more effective benchmark in the long run. A suitable venue for this 'calibration' exercise may be a new subcommittee on 'daylighting metrics' that has recently been commissioned by the Illuminating Engineering Society of North America (IESNA).

5.3 MODELING MANUAL BLIND CONTROL

Modeling manual blind control is notoriously difficult. Nevertheless, it is an important aspect of a dynamic metric since venetian blinds are the most common shading device type found in commercial and residential spaces throughout North America and Europe. Blinds are very effective at reducing glare but they also reduce the daylight available indoors. The current generation of field-study-based blind models tend to overestimate the use of blinds, because the 'triggers' that prompt an occupant to *close* the blinds have been clearly identified whereas the ones to *open* them have not. Another remaining model uncertainty is how slat angles are set when the blinds are closed. While fully acknowledging these limitations of current models, the authors recommend their use over not taking blinds into account at all. Also, a conservative estimate is generally better than an overestimate that cannot be met in reality.

Manual blind control is also important when assessing view to the outside for different design variants. If the venetian blinds for one variant are a lot more often closed than for a competing option, the building occupants for the former option will routinely end up with less or no view. This argument suggests that the view credit in LEED should be combined with an estimate of the percentage of occupied hours per year when the view might actually be available. In practice this would provide no additional simulation work for the design team if the daylight factor credit were also to be replaced with a dynamic performance metric.

5.4 CONCLUSION

While this paper focused on dynamic performance metrics and their ability to capture the 'architectural' dimension of daylighting, we do not suggest that these metrics can predict holistic 'good' daylighting. Nor do we place any value judgment on the architectural definition of daylighting over the other definitions in Table 1. A well daylit space should host a stimulating interplay of light and building form that satisfies occupant needs by keeping them comfortable. At the same time, overall electric lighting loads should be low and solar gains controlled. As mentioned earlier in this document, these qualities reveal themselves as energy savings in whole-building energy efficiency metrics. In the long run, all of these requirements should lead to a set of daylight performance metrics that each describe different aspects of daylighting design and that all have to be met synchronously for a space to receive an overall 'good' rating for daylight.

Finally, a metrics-based approach to daylighting design is intrinsically limited. The ultimate success of a daylit space, the 'sparkle' that makes it a pleasure for the eye and speaks to the soul, makes daylighting an art as much as a science. For aspects that *can* be addressed by metrics, this paper presented alternatives to the daylight factor, and it is the authors' hope that it will contribute to the ongoing discussion of where daylighting design practice should go in the future.

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